

Universitat de Lleida

Document downloaded from:

<http://hdl.handle.net/10459.1/65077>

The final publication is available at:

<https://doi.org/10.1002/hyp.5919>

Copyright

(c) Wiley, 2006

**A SIMPLE PARAMETERIZATION OF BULK CANOPY RESISTANCE FROM CLIMATIC
VARIABLES FOR ESTIMATING HOURLY EVAPOTRANSPIRATION**

Corresponding author:

Pedro J. Perez

Dpto. de Medio Ambiente y Ciencias del Suelo, E.T.S Ingenieria Agraria.

Av. Rovira Roure, 191. 25198 - Lleida, Spain.

E-mail adress: P.J.Perez@macs.udl.es

Tel.: +34 973 702614

Fax: +34 973 702613

A SIMPLE PARAMETERIZATION OF BULK CANOPY RESISTANCE FROM CLIMATIC VARIABLES FOR ESTIMATING HOURLY EVAPOTRANSPIRATION

P.J. Perez⁽¹⁾, S. Lecina⁽²⁾, F. Castellvi⁽¹⁾, A. Martínez-Cob⁽²⁾ and F.J. Villalobos⁽³⁾

⁽¹⁾ Dpto. de Medio Ambiente y Ciencias del Suelo, Universidad de Lleida, Av. Rovira Roure, 191, 25198 Lleida, Spain.

⁽²⁾ Laboratorio de Agronomía y Medio Ambiente (DGA-CSIC), Dpto. de Genética y Producción Vegetal (EEAD), Apdo. 202, 50080 Zaragoza, Spain.

⁽³⁾ Instituto de Agricultura Sostenible (CSIC) and Dep. Agronomía, Universidad de Córdoba, Apdo. 4084, 14080 Córdoba, Spain.

ABSTRACT

This paper examines a model for estimating canopy resistance (r_c) and reference evapotranspiration (ET_o) on an hourly basis. The experimental data refer to grass at two sites in Spain with semiarid and windy conditions in a typical Mediterranean climate. Measured hourly ET_o values were obtained over grass during a four year period between 1997 and 2000 using a weighing lysimeter (Zaragoza, NE Spain) and an eddy covariance system (Córdoba, S Spain). The present model is based on the Penman-Monteith (PM) approach, but incorporates a variable canopy resistance r_c as an empirical function of the square root of a climatic resistance r^* that depends on climatic variables. Values for the variable r_c were also computed according to two other approaches: with the r_c variable as a straight line function of r^* (Katerji and Perrier, 1983), and also as a mechanistic function of weather variables as proposed by Todorovic (1999).

In the proposed model, the results showed that the ratio r_c/r_a (where r_a is the aerodynamic resistance) presents a dependence on the square root of r^*/r_a , as the best approach with empirically derived global parameters. When estimating hourly ET_o values, we compared the performance of the PM equation using those estimated variable r_c with the PM equation as proposed by the FAO, with a constant r_c value equal to 70 s m^{-1} . The results confirmed the relative robustness of the PM method with constant r_c , but also revealed a tendency to underestimate the measured values when ET_o is high. Under the semiarid conditions of the two experimental sites, slightly better estimates of ET_o were obtained when a estimated variable r_c was used. Although the improvement was limited, the best estimates were provided by the Todorovic and the proposed method. The proposed approach for r_c as a

function of the square root of r^* may be considered as an alternative for modeling r_c , since the results suggested that the global coefficients of this locally calibrated relationship might be generalized to other climatic regions. It may also be useful to incorporate the effects of variable canopy resistances into other climatic and hydrological models.

Keywords: variable canopy resistance, evapotranspiration, Penman-Monteith equation, grass

1. INTRODUCTION

Evapotranspiration is a component of the hydrological cycle whose accurate computation is needed for an appropriate management of water resources. A high degree of accuracy in the estimation of crop evapotranspiration may lead to important savings in water requirements in irrigated areas. The Food and Agriculture Organization (FAO) proposed a methodology for computing crop evapotranspiration (Doorenbos and Pruitt, 1977), based on the use of reference evapotranspiration (ET_o) and crop coefficients (K_c). Allen *et al.* (1998) redefined the concept of ET_o and adopted the Penman-Monteith (PM) equation with constant canopy resistance (r_c) to estimate reference evapotranspiration.

The PM model has been applied in different regions of the world and has provided good results in comparison with other equations (Berengena *et al.*, 2001; Hussein, 1999; Ventura *et al.*, 1999; Allen *et al.*, 1994a, b; Jensen *et al.*, 1990; Allen *et al.*, 1989). However, many of these studies suggest that in semi-arid and windy areas with a high evaporative demand, there is a tendency for the PM method to underestimate the higher values of measured ET_o , and to overestimate the lower ET_o values. The extent of this underestimation may range from 2% to 18% (Pereira *et al.*, 1999; Todorovic, 1999; Ventura *et al.*, 1999; Steduto *et al.*, 1996).

The accuracy of the predictions of the PM model may be constrained by such simplifying assumptions as the 'big leaf' approximation with constant canopy resistance. Given the driving meteorological variables at a particular site, estimates made with the PM equation rely on the correct modeling of the effective values of two parameters: aerodynamic resistance r_a and bulk (surface) canopy resistance r_c . The FAO has adopted a standard PM equation that can be applied worldwide, using a constant value of 70 s m^{-1} for r_c when calculating grass reference evapotranspiration (Allen *et al.*, 1998; Allen *et al.*, 1994a, b; Smith *et al.*, 1991). However, this fixed value for r_c may be the cause of the previously mentioned tendency for the Penman-Monteith equation to underestimate ET_o (Rana *et al.*, 1994). As r_a can be calculated from meteorological conditions, in order to provide more accurate estimations of evapotranspiration using the PM equation, it may be necessary to parameterise canopy resistance as a primary factor in the evapotranspiration process (Monteith, 1965).

The net resistance to diffusion through the crop and soil surfaces is represented by the bulk surface resistance r_c . This is not only a physiological parameter but also has an aerodynamic component (Alves *et al.*, 1998). It is not easy to estimate r_c for different climatic and crop water conditions as it is influenced by solar radiation, temperature, vapor pressure deficit and soil water

content (Pereira et al., 1999; Alves et al., 1998; Huntingford, 1995; Kim and Verma, 1991; Noilham and Planton, 1989; Jarvis, 1976; Perrier, 1975). Even so, a simple method for modeling this resistance may yield a better estimation when the PM equation is applied over both short and tall crops (Alves and Pereira, 2000; Pereira et al., 1999; Kelliher et al., 1995; Rana et al., 1997, 1994) and over other type of vegetation (Sommer et al., 2002; Monteith, 1995; Linacre, 1993). It could also be useful to incorporate the effects of the resistance due to vegetation into climatic and hydrological models (Crawford et al., 2000; Dickinson et al., 1991).

The Jarvis's multiplicative model (1976) is one of the approaches to estimate bulk canopy resistance. This model relates r_c , as computed by inverting the PM equation, and several climatic variables. However, this procedure only includes the physiological component of r_c , and does not consider the aerodynamic component (Alves and Pereira, 2000). Todorovic (1999) has recently developed a new model to compute a variable r_c that does not require any calibration. When it is applied to estimate hourly ET_o with the PM equation, results exhibited a better adjustment to measured ET_o than using a fixed r_c value (Lecina et al., 2003; Todorovic, 1999). Katerji and Perrier (1983) proposed a linear model in which r_c depends on climatic variables and aerodynamic resistance. After a previous calibration, this model has been tested and has yielded good results for practical purposes for a limited range of Bowen ratio values (Alves and Pereira, 2000; Rana and Katerji, 2000; Pereira et al., 1999; Rana et al., 1994).

However, the linear relationship represented by the Katerji and Perrier (1983) approach contains two parameters that are actually dependent on the Bowen ratio (β) value: a factor that it is not readily available. Over short periods of time it is expected to find only limited variations in the values of these two parameters (Alves and Pereira, 2000). In an attempt to avoid this dependence on β , we explored simple parametric models (based on the Katerji and Perrier approach) that relate canopy resistance to available meteorological data, in order to find the best approach involving global empirical parameters for any range of β values. The next objective was to assess the behaviour of the PM method when a variable r_c was estimated according to the previous approaches, and to evaluate whether the use of these variable rather than fixed r_c values would improve the hourly ET_o estimates obtained by the PM equation. Experimental measurements were carried out in two different regions: the Ebro and Guadalquivir valleys (Spain), which contain around 42 % of Spain's total irrigated land. They correspond to semiarid conditions and exhibit high evaporative demand, particularly in summer. Evapotranspiration estimates were compared with measured values using a weighing lysimeter (Ebro River valley) and an eddy covariance system (Guadalquivir River valley).

2. THEORETICAL CONSIDERATIONS

The Penman-Monteith combination model represents a basic general description of the evaporative process from a vegetative surface. It is expressed as (Allen et al., 1998):

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p (e^* - e) / r_a}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \quad (1)$$

where λE is the latent heat flux density (W m^{-2}), R_n and G are respectively the net radiation and soil heat flux (W m^{-2}), Δ is the saturation vapor pressure slope ($\text{Pa } ^\circ\text{C}^{-1}$), ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of moist air ($\text{J kg}^{-1} ^\circ\text{C}^{-1}$), e^* and e are respectively the saturation and actual vapor pressure of the air (Pa), γ is the psychrometric constant ($\text{Pa } ^\circ\text{C}^{-1}$), r_a is the aerodynamic resistance (s m^{-1}), and r_c is the canopy or bulk surface resistance (s m^{-1}). r_a is the resistance to the turbulent transfer of vapor between the source and the reference level (Fig. 1). The source of vapor is at height $d+z_{oh}$, which is considered the effective crop surface (Allen et al., 1998) where d (m) is the zero-plane displacement and z_{oh} (m) is the roughness length for heat. r_c is the bulk surface resistance of the entire vegetation canopy considered as a 'big leaf' (taken as the parallel sum of the stomatal resistances) or simply the canopy resistance.

This single-layer or 'big leaf' model (Allen et al., 1998; Monteith and Unsworth, 1990) assumes that the latent heat lost by a crop is controlled by the bulk surface resistance, which represents the resistance of the whole canopy to the diffusion of water vapor from leaves to the atmosphere as a result of stomatal regulation. It is influenced by climatological and agronomical variables such as the structure of the canopy. Evaporation is initially governed by the difference between the saturated vapor pressure within the stomata and the vapor pressure outside them. Furthermore, the process depends on the opening of the stomata by means of the stomatal resistance of a single leaf r_l . For a vegetated surface, r_c is the combined resistance of all the leaves and of the soil surface, and the resistance to vapor transfer inside the canopy from these surfaces up to the 'big leaf' (Fig. 1). Thus, it can be considered that r_c has an indirectly aerodynamic component (Alves et al., 1998), although it is commonly assumed that r_c mainly represents a stomatal response. The resistance of the soil surface depends on the specific soil moisture conditions, while for an open water surface this resistance is zero (Berkowicz and Prahm, 1982).

The model proposed by Jarvis (1976) suggested that the environmental factors governing the stomatal resistance r_l could be treated individually, by considering the stomatal conductance of a single leaf as a product of several functions. Each normalized function depends on one variable: solar

radiation, temperature, vapor pressure deficit, leaf area index or soil moisture (Allen et al., 1996). This multiplicative model only includes the physiological component of r_c but not the aerodynamic component, and each of the empirical functions contains one or more of the constants which must be determined previously (Kelliher et al., 1995; Monteith, 1995). Finally, it must be added that the model assumption that meteorological variables operate independently remains open to question.

The PM equation contains both a radiative and an aerodynamic term. Over a very large homogeneous, moist surface and under steady conditions, e tends to the saturation value e^* and $r_c \ll r_a$. Consequently, the first term on the right or radiative term in Eq. (1) with $r_c \approx 0$, which is often described as the 'equilibrium' evaporation $\lambda E_e = [\Delta/(\Delta + \gamma)](R_n - G)$ (Pereira et al., 1999; Monteith and Unsworth, 1990), may be considered as the lower limit of evaporation from moist surfaces. The aerodynamic term or second term on the right in Eq. (1), is therefore a measure of the departure from equilibrium in the atmosphere. The atmospheric boundary layer is hardly ever uniform and tends to maintain a humidity deficit, even over the oceans. Thus, equilibrium is rarely observed over a wet surface and the success of the PM model for estimating evapotranspiration may depend on the accurate modeling of average surface resistance r_c .

Taking the equilibrium evaporation as a common factor, Eq. (1) can be written in the form

$$\lambda E = \frac{\Delta(R_n - G) \left[1 + \frac{\rho_a c_p (e^* - e)/r_a}{\Delta(R_n - G)} \right]}{(\Delta + \gamma) + \gamma \frac{r_c}{r_a}}$$

and after rearranging

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1 + \frac{\rho_a c_p (e^* - e)}{\Delta(R_n - G) r_a}}{1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a}} \quad (2)$$

On the right-hand side of the expression, the numerator can be expressed in the same way as the denominator, by defining a climatic resistance given as

$$r^* = \frac{\Delta + \gamma}{\gamma} \frac{\rho_a c_p (e^* - e)}{\Delta(R_n - G)} \quad (3)$$

so that, through substitution in Eq. (2) we obtained

$$\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1 + \frac{\gamma}{\Delta + \gamma} \frac{r^*}{r_a}}{1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a}} \quad (4)$$

Parameter r^* is related to the isothermal resistance first introduced by Monteith (1965) and represents the surface resistance for equilibrium evaporation, because in Eq. (4) $\lambda E = \lambda E_e$ for $r_c = r^*$ (Pereira et al., 1999; Rana et al., 1997; Huntingford, 1995). The value of r^* mainly depends on climatic characteristics, although R_n and G are also influenced by the characteristics of the vegetative surface. The term r^* can be called the *climatic resistance* for the surface.

Equation (4) depends on time, but in practice meteorological variables are measured continuously and averaged on a half-hourly or hourly basis, so the model can still be applied. The fraction on the right-hand side of Eq. (4) is a dimensionless quantity that can be considered as a crop-climatological coefficient. Perrier et al. (1980) and Katerji and Perrier (1983) showed that a link existed between r_c/r_a and r^*/r_a which depends on phenological state and soil water status. They proposed a linear relationship between these variables based on a dimensional analysis, while Rana et al. (1997, 1994) presented experimental results for reference crops such as grass and alfalfa in a Mediterranean climate.

The approach proposed by Katerji and Perrier (1983) is a linear link with the form $r_c/r_a = a + b(r^*/r_a)$. Parameters a and b can be empirically calibrated but, as pointed out by Alves and Pereira (2000), the model is constrained by the fact that they actually depend on the temporary value of the Bowen ratio β . Therefore, the empirical calibration should actually be made on β , the only factor that is not readily available. For practical purposes, this needs to be measured or estimated, though for well watered crops and over short periods of time β is not expected to exhibit great variations. To avoid this dependence on β , and taking the Katerji and Perrier approach as a base, it is possible to explore any linear model that relates canopy resistance r_c to r^* . Our aim was to find the best approach for making estimations based on global empirical parameters, if they exist, that are valid for any range of β values. These parameters will therefore be representative of the crop for any climatic conditions. With r_c calibrated empirically and locally as a function of r^* , only standard meteorological variables are required to estimate the bulk surface resistance.

3. MATERIALS AND METHODS

3.1. Site description and data

This study was conducted at two locations that are representative of the central areas of the Ebro and Guadalquivir river valleys (which contain around 42% of Spain's total irrigated land) and lie in the provinces of Zaragoza and Córdoba (Figure 2). In the case of the Ebro site, the study was conducted at an experimental farm (225 m asl, 41° 43' N, 0° 49' W) located on the terraces of the river Gállego, in Zaragoza province, and about 8 km north of the confluence with the river Ebro. Average annual precipitation is about 330 mm, and is mostly recorded in spring and autumn, though storm precipitation is also relatively frequent in summer. Average annual temperature is about 15 °C. The area is one of the windiest in Spain. Measurements were taken over a 1.2 ha plot with uniform grass cover (*Festuca arundinacea* Moench.). The plot was regularly irrigated and cut throughout the year so that its conditions resembled those of the reference standard as closely as possible

A weighing lysimeter, 1.7 m in depth and covering a 6.3 m² effective surface area, was located at the centre of the plot. A load cell connected to a datalogger (CR500, Campbell Sci. Inc.) recorded lysimeter mass losses at 0.5 s intervals. These data were used to derive hourly evapotranspiration rates. The combined resolutions of the load cell and the datalogger made it possible to detect mass losses of about 0.3 kg (0.04 mm water depth). Measurements were taken from March to October 1999 and from March to September 2000. Only days without incidences (irrigation, rainfall, lysimeter drainage and grass cutting), when measured grass height was between 0.10 and 0.15 m, were used for analyses.

An automatic weather station (CR10, Campbell Sci. Inc.) close to the lysimeter, recorded hourly averages for air temperature and relative humidity (HMP35D, Vaisala), and net radiation (Q-7, REBS) at a height of 1.5 m. Wind speed and direction were measured at a height of 2.0 m (switching anemometer A100R and wind vane W200P, Vector Instr.). The soil heat flux was measured using two plates (HFT1, REBS) buried at a depth of 8 cm and using an averaging soil temperature probe placed between 2 and 6 cm in depth (Allen et al., 1996).

In the Guadalquivir valley, the study was conducted at an experimental farm (70 m asl, 37° 51' N, 4° 51' W) located on the terraces of the Guadalquivir river, near Córdoba. Average annual precipitation is about 600 mm and is mainly recorded in winter, spring and autumn, with hardly any rainfall in summer. Average annual temperature is about 17 °C. Advective conditions during summer are more frequent than in Zaragoza, but the area is significantly less windy than the middle section of

the Ebro river valley. Measurements were taken over a 1.3 ha plot with uniform grass cover, regularly irrigated and cut all year round. The measurement periods were from July to October 1997 and from July to August 1998. Only days on which measured grass height was between 0.10 and 0.15 m were used for analyses.

An eddy covariance system (Campbell Sci. Inc.) was located at the centre of the plot to measure evapotranspiration. The sensors used included a krypton hygrometer (model KH20), a single-axis sonic anemometer (model CA27), and two fine-wire thermocouples (models 127 and TCBR-3), which were attached to the two previously mentioned sensors. The hygrometer and the sonic anemometer were installed at a height of 0.32 m, in order to maintain a height:fetch ratio of more than 100. They were oriented towards the west, which was the predominant wind direction, and were placed 10 cm apart in direction north-south. Measurements of fluctuations in water vapor density, vertical wind speed and air temperature were recorded every 0.1 s and averaged every 10 minutes. These readings were used to obtain hourly measured latent heat flux values as described by Villalobos (1997), which were then transformed to hourly ET_o rates (Allen et al., 1998). An automatic weather station (CR10, Campbell Sci. Inc.), located close to the eddy covariance system, recorded standard meteorological variables in the same way as in the Ebro river valley.

3.2. Evapotranspiration estimation

a. Constant canopy resistance: Penman-Monteith equation

The PM equation is given by Eq. (1). The important assumption behind this model is that, despite the variations within the canopy itself, the behaviour of all the stomata considered together is comparable with that of a single 'big leaf' from which heat and vapor escape. This 'big leaf' is located at a height $d+z_{oh}$, where d is the zero-plane displacement height and z_{oh} is the roughness length for heat (Fig. 1). In this paper, measured rather than estimated R_n and G values were used. This was done in order to prevent potential uncertainties derived from the estimation of these two variables affecting the analysis involving the use of fixed and variable r_c values. Units and computations (except R_n and G) in Eq. (1) followed Allen et al. (1998), r_c was considered constant and equal to 70 s m^{-1} and grass height was set to 0.12 m. Throughout the study period, Eq. (1) was applied to obtain hourly ET_o estimates using hourly averages of meteorological variables.

For the following two models, the data set available for each location was divided into two groups: a calibration data set and a validation data set. Available days were organised by date and one of three days was selected for calibration, while the other two were selected for validation.

b. Todorovic method

This model is a new approach for modeling canopy resistance: it is based on the 'big leaf' approach but incorporates a variable r_c . The model's input requires only standard meteorological data as in the PM combination approach. A full discussion of the theory and assumptions of the model can be found in Todorovic (1999). Here, we simply present the equations used to obtain the variable r_c values. Todorovic (1999) considers a climatological resistance r_i defined by:

$$r_i = \frac{\rho_a c_p (e^* - e)}{\gamma(R_n - G)} \quad (5)$$

as used in the literature (Monteith and Unsworth, 1990; Monteith, 1965). This resistance, as seen by comparison with Eq. (3), is

$$r_i = [\Delta / (\Delta + \gamma)] r^* \quad (6)$$

Then, Todorovic (1999) uses r_i and r_a , defined according to Allen et al. (1998), to set the following 2nd degree equation

$$aX^2 + bX + c = 0 \quad (7)$$

a function of $X = r_c/r_i$, where the parameters are defined by

$$\begin{aligned} a &= \frac{\Delta + \gamma (r_i/r_a)}{\Delta + \gamma} (r_i/r_a) (e^* - e) \\ b &= -\gamma \left(\frac{r_i}{r_a} \right) \frac{\gamma e^* - e}{\Delta \Delta + \gamma} \\ c &= -(\Delta + \gamma) \frac{\gamma e^* - e}{\Delta \Delta + \gamma} \end{aligned} \quad (8)$$

Solving for Eq. (7), which has only one positive solution, the variable canopy resistance is obtained as $r_c = X r_i$. Eqs. (7) and (8) were applied to the validation data set to obtain hourly estimates of canopy resistance ($r_{c,TD}$) using the hourly averages of meteorological variables. A fixed value of $r_c = 200 \text{ s}^{-1}$ was considered for night hours. These variable r_c values were then used, assuming a grass height of 0.12 m, to obtain hourly ET_o estimates by directly applying the PM equation (Eq. (1)).

Preliminary testing of this approach has provided convincing results obtained on an hourly basis (Todorovic, 1999).

c. Variable canopy resistance: semiempirical approach

Based on the experimental relationship found by Perrier et al. (1980) between the bulk canopy, aerodynamic and climatological resistance r^* (Eq. (3)), several authors proposed a model in which r_c/r_a is a linear function of r^*/r_a . This model has been applied to wheat (Perrier et al., 1980), grass and alfalfa (Steduto et al., 2003; Rana et al., 1994; Katerji and Perrier, 1983), tomato (Katerji et al., 1988) and rice (Peterschmitt and Perrier, 1991). The coefficients of those linear relationships depend on the type of crop, its phenological state or soil water status (Rana et al., 1997).

In order to analyse this simple model, we propose exploring a functional relationship of the form

$$\frac{r_c}{r_a} = a + b f\left(\frac{r^*}{r_a}\right) \quad (9)$$

for the reference crop, where a and b are global parameters that are to be determined empirically. When Eq. (9) is substituted into Eq. (4), the Penman-Monteith model contains only standard climatological variables.

The most commonly used formulations for estimating aerodynamic resistance r_a , consider that apparent sources of heat and vapor within the canopy are at a lower level than the apparent sink of momentum (Monteith and Unsworth, 1990). In the PM equation the big leaf is implicitly located at the height $d + z_{oh}$, where z_{oh} (m) is the roughness length for sensible heat transfer. When the leaves at the top of the canopy, between $d + z_{oh}$ and crop height h_c , are the most important source of vapor flux, the use of the $d + z_{oh}$ level as the evaporative surface can lead to an overestimation of r_a and to negative values for bulk surface resistance r_c when it is computed by inverting the PM equation. To avoid this, r_a can be computed between the top of the canopy h_c and the reference height in the atmosphere as (Alves et al., 1998; Perrier, 1975)

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right) \ln\left(\frac{z_h - d}{h_c - d}\right)}{k^2 u_{zm}} \quad (10)$$

where z_m and z_h are the wind and air temperature measurement heights, respectively, h_c is the crop height, k is the dimensionless von Karman constant, and u_{zm} is the wind speed measured at height z_m .

The term $h_c - d$ substitutes the roughness length for heat transfer used to compute r_a according to Allen et al. (1998).

So, for both the calibration and the validation data set, the experimental or measured hourly values of bulk surface resistance r_c ($s\ m^{-1}$) were obtained by inverting the PM equation (top-down approach) as

$$r_c = r_a \left[\frac{\Delta}{\gamma} \frac{R_n - G}{\lambda E} - \frac{\Delta + \gamma}{\gamma} \right] + \frac{\rho c_p}{\gamma} \frac{D}{\lambda E} \quad (11)$$

where D is the vapor pressure deficit (Pa) ($D = e^* - e$ in Eq. (1)), $R_n - G$ is the available energy for the entire surface ($W\ m^{-2}$) and λE is the latent heat flux ($W\ m^{-2}$) measured by a lysimeter (Zaragoza) or by an eddy covariance system (Córdoba).

The hourly values measured for $R_n - G$, D and λE were used to compute hourly r_c values in Eq. (11), aerodynamic resistances in Eq. (10) and climatic resistances in Eq. (3). Using only the calibration data sets for Zaragoza and Córdoba, several simple relationships between r_c/r_a and r^*/r_a for any range of β values were analyzed for the reference crop. The calibrated values of parameters a and b in Eq. (9) allowed us to obtain, using only the validation data set, an estimated variable canopy resistance $r_{c,est}$. This was then used to estimate hourly evapotranspiration values (λE_{est}) from Eq. (1) or Eq. (4).

3.3. Statistical methods

In the evaluation of the different relationships represented by Eq. (9), the ability to predict r_c has been compared using the coefficient of determination R^2 as the measure of the goodness of fit, that is, of the performance of the model; R^2 is a measure of the total variance accounted for by the model. Parameters a and b in Eq. (9) are then obtained for the best fit using the calibration data set.

A complication arises when the model that maximizes R^2 for r_c may not maximize it when predicting evapotranspiration ET . Once the best parameterization of r_c had been chosen and the optimum coefficient values in Eq. (9) had been found, comparisons between measured and estimated hourly ET values were carried out using the three models above. To test which of the resulting models was significantly better than the others, a simple linear regression between the predicted and the observed values was made, based on the criterion of trying to maximize R^2 . Nevertheless, in order to make a better quantitative comparison between the models, predicted results can be evaluated with

reference to several statistics (Alexandris and Kerkides, 2003; Lee and Singh, 1998; Verhoef et al., 1997; Mayer and Butler, 1993; Willmot, 1981, 1982).

The first statistic is the bias or mean deviation error, $MBE = [\sum (O_i - P_i)]/n$. The second is the root mean square error, $RMSE = \sqrt{\sum (O_i - P_i)^2 / n}$, which is considered as a better indicator of model performance than the correlation statistics. They can be expressed as percentages of the mean observed value (relative $RMSE(\%) = 100 RMSE / \bar{O}$). In the above expressions, P_i and O_i represent the predicted (estimated) and observed (measured) values, n is the total number of data and \bar{O} is the mean of observed data. RMSE provides a measure of the total difference between the predicted and observed values. The closer RMSE is to zero, the better the prediction.

The statistic we will use as the model selection criterion is the modeling efficiency (Lee and Singh, 1998) defined as $EF = 1 - [\sum (O_i - P_i)^2] / [\sum (O_i - \bar{O})^2]$, which is similar to the index of agreement (Willmot, 1982). Modeling efficiency is a dimensionless statistic that measures the fraction of the variance of the observed values which is explained by the model, so it provides a good measure of the model's performance. The best model is the one with a value of EF closest to 1 and with the lowest RMSE.

4. RESULTS AND DISCUSSION

The values of the statistics derived from air temperature and wind speed records for Zaragoza and Córdoba during the measurement periods are presented in Table 1. They are shown for descriptive purposes because, as a result of the different measurement periods, it was not possible to compare them directly. It should be noted that on 9% of the days at Zaragoza the average daily wind speed was greater than 4 m s^{-1} , whereas this did not occur at Córdoba. As previously mentioned, Zaragoza is located within one of the windiest areas in Spain.

The hourly values of r_a obtained with Eq. (10) were lower than those obtained using the classical expression in the PM equation for the reference grass (Allen et al., 1998). This confirmed results obtained by other authors over both short and tall vegetation (Hall, 2002; Alves et al., 1998). For these authors, aerodynamic resistance using the classical logarithmic profile equations for momentum exchange results in estimates that are systematically higher than values derived from direct

measurements. The differences in the estimations of r_a for dense or sparse canopies or even for grass, are, as reviewed by Verhoef (1995), the result of the problem of the parameterization of an excess resistance. Figure 3a shows the daily evolution of r_a for a typical day at Zaragoza.

As described elsewhere in the literature, bulk surface resistance is small and tends to remain relatively constant on average from 8h to 14h. After this, r_c tends to increase gradually in the afternoon reflecting the daily course of the environmental variables that influence it (Fig. 3b). Negative values have been obtained for r_c independently of the time of day, but these have mainly been registered early in the morning and at night, when the available energy ($R_n - G$) tends to be small and with negative values and when the vapor pressure deficit (D) is also small. In well irrigated crops, factors external to the crops control the latent heat flux to a greater extent than purely physiological factors.

When a constant r_c is considered, Table 2 shows the results of comparisons between the estimated and measured hourly values for evapotranspiration at the two locations, based on the validation data set for each measurement period. ET_{PM} represents the estimated values obtained using the Penman-Monteith equation (Eq. (1)) with a fixed value of $r_c = 70 \text{ s m}^{-1}$. The values for modeling efficiency (EF) suggest good agreement for the method at both locations, with a relatively small scatter of data but with a slope lower than one (Table 2). There is a tendency for the PM method to overestimate low values of measured ET_o and to underestimate high ET_o values (Fig. 4). This behaviour has already been reported at other Mediterranean locations (Steduto et al., 2003, 1996).

The underestimation of high ET_o values was smaller in Córdoba than in Zaragoza. This might have been due to the use of an eddy covariance system for measuring latent heat flux. This system, depending on the horizontal sensor separation and on measurement height, may underestimate evapotranspiration (Villalobos, 1997). Another reason for the differences in results between the two locations may be their different wind conditions. In Zaragoza, the agreement between lysimeter and ET_{PM} values was found to decrease as wind speed increased. Under conditions of high evaporative demand (sunny days in summer), evapotranspiration rates are expected to further increase under windy conditions. In such situations, the PM method with constant r_c is relatively robust, but seems to provide an insufficient representation of latent heat flux to the atmosphere. This method led to an underestimation of high ET_o values in both zones under semiarid conditions (Steduto et al., 2003, 1996; Ventura, 1999; Rana et al., 1994).

Since one of our aims was to analyse the performance of the PM equation with respect to different ways of considering canopy resistance, we have analysed the mechanistic approach

represented by Eqs. (7) and (8) (Todorovic, 1999). The variable canopy resistance estimated with this method $r_{c,TD}$ was then applied to the PM equation (Eq. (1)) and hourly estimates of evapotranspiration ET_{TD} were obtained. The values of $r_{c,TD}$ in the Todorovic method only depend on weather variables and do not require calibration, they can therefore be directly applied to the validation data set for each measurement period at both sites. For the diurnal period, the values of $r_{c,TD}$ were, on average, 10% lower than the experimental values r_c but, as shown in Fig. 5a, with a high degree of variability in the case of Zaragoza.

The drawback of the Todorovic method is that it can-not be generally applied for the nocturnal period when both vapor pressure deficit D and available energy R_n-G are low or close to zero. In such cases both r_i (Eq. (5)) and r^* have negative or non-defined values, so the solutions for X in Eq. (7) and r_c are not defined. This model can only be applied when r_i is positive, and therefore for cases when $r_i \leq 0$ (usually at night) a fixed value of $r_{c,TD} = 200 \text{ s m}^{-1}$ must be considered (Allen et al., 1998). When the variable canopy resistance $r_{c,TD}$ was used in Eq. (1), estimated hourly values ET_{TD} for evapotranspiration were obtained.

Results for the comparison between estimated ET_{TD} and measured ET_o values are presented in Table 2 and Fig. 5b. The statistics showed that the relative RMSE(%) of estimates for ET_{TD} was about 3% lower than that for ET_{PM} , and that the slope of the linear regression with measured values for ET_{TD} was closer to 1 than for ET_{PM} . Furthermore, the relative mean deviation error (MBE(%)) indicated that ET_{TD} tends to globally underestimate measured values less than ET_{PM} does, as shown in Fig. 5b with respect to high evaporative demand. Even in Córdoba ET_{TD} tends to globally overestimate measured ET_o (negative MBE, Table 2). The values for the modeling efficiency taken together with the above results indicate that estimation of evapotranspiration using the Todorovic method (variable r_c) shows better performance than the PM method (fixed r_c). Thus, if there is a need to incorporate the effect of a variable r_c , the Todorovic method may be useful at least under the semiarid and windy conditions such as those of the Ebro river valley. Results cited in a previous work (Lecina et al., 2003) showed that daily ET_o estimates could be obtained with sufficient accuracy using the PM method.

The second way to estimate a variable r_c is through the semi-empirical approach given by Eq. (9) which relates r_c/r_a to r^*/r_a . Results found by others authors (Steduto et al., 2003; Alves and Pereira, 2000; Rana et al., 1997) seem to show a linear relationship between these variables on an hourly basis. These results were generally obtained under certain limitations corresponding to the diurnal period, or were obtained for a limited range of Bowen ratio β values. Alves and Pereira (2000) found such

results for β values in the interval $[-0.3, 0.3]$, corresponding to situations when crop evapotranspiration was maximum and when available energy R_n-G had values corresponding to the middle of the day.

We carried out an analysis of the empirical relationship provided by Eq. (9) for our semiarid regions with the aim of amplifying this data interval and thereby covering the largest possible range of situations throughout the day, with the following results. Working with the complete set of calibration data for the two measurement zones, we found that a straight line did not represent the best relationship between r_c/r_a and r^*/r_a . This result was obtained independently of the interval of β values considered. When latent and sensible heat fluxes are measured over grass on an hourly basis, 85% of the actual values for β lie in the interval $[-0.5, 0.5]$ throughout the day (Perez et al., 1999). As seen in Fig. 6a, when considering cases in which the β values are between $[-0.5, 0.5]$, the functional form of the dependence of r_c/r_a on r^*/r_a departs from linearity. It seems that r_c/r_a tends to some saturation value when r^*/r_a increases. As in this case we are including data corresponding to a longer diurnal period (07h to 19h) in our analysis, this result extends that reported by Alves and Pereira (2000).

The main drawback is that for the nocturnal period when vapor pressure deficit D and available energy R_n-G are low, as at sunrise and sunset, the canopy resistance r_c may register very high positive or very low negative values and the climatic resistance r^* may register negative or non-defined values. For these situations and for comparison with the Todorovic model, when $r^* \leq 0$ we have considered a fixed value of 200 s m^{-1} for r_c . Even so, about $\pm 5\%$ is a typical error associated with the measurement of net radiation, while the resolution of the weighing lysimeter is 0.04 mm in the measurement of evapotranspiration. Therefore, the next step was to use in the analysis only the calibration data when $R_n-G \geq 30 \text{ W m}^{-2}$ and when measured $ET_o \geq 0.04 \text{ mm h}^{-1}$, independently of β values. In consequence this constraint effectively limited the analysis to the diurnal period going from 07h to 19h (Fig. 6b), but with β values ranging from -0.8 to 2.0 .

Table 3 shows the values of the empirical coefficients locally calibrated for each analysed relationship. Results show that the best-fit relationship corresponded to a dependence of r_c/r_a on the square root of r^*/r_a and not to a linear relationship, as the coefficient of determination R^2 indicates (Table 3). For the linear dependence $(r_c/r_a)_{est,2}$, it can be observed that the values of the empirical coefficients for our semiarid zones ($a_2 = 1.1$, $b_2 = 0.19$), are similar to those obtained by Steduto et al. (2003) for grass in southern Italy ($a_5 = 0.918$, $b_5 = 0.18$). This finding also suggests that it may be possible to extrapolate the empirical coefficients of the proposed method $(r_c/r_a)_{est,1}$ (Table 3) to other climatic regions.

The statistics used for the comparison between estimated and experimental values of r_c/r_a , reported in Table 3 for the global set of calibration days at Zaragoza and Córdoba, indicate that for method $(r_c/r_a)_{est,1}$ relative RMSE is 13% lower and the modeling efficiency is higher than when using the estimating method $(r_c/r_a)_{est,2}$. Although the Todorovic method does not need any previous calibration, the statistics show that $r_{c,TD}$ generally underestimates values of canopy resistance obtained by inverting the PM equation (MBE = 37.3%). This is mainly true for values of canopy resistance that exceed 50 s m^{-1} . Once empirically calibrated for our semiarid regions, the method $(r_c/r_a)_{est,1}$ performed better when estimating canopy resistance.

The variable r_c estimated through the proposed methods $(r_c/r_a)_{est,1}$ and $(r_c/r_a)_{est,2}$ was used in Eq. (1) to estimate hourly values of evapotranspiration $ET_{est,1}$ and $ET_{est,2}$, respectively. Table 4 shows the results of the comparison between the four estimating methods and the measured ET_o values for the global set of validation days at Zaragoza and Córdoba. As seen, the relative RMSE of estimates for $ET_{est,1}$ is about 2% lower than for ET_{PM} , and the slope of the linear regression with measured values is closer to 1 for $ET_{est,1}$ than for ET_{PM} (Fig. 7). Overall, these results indicate that the proposed method $ET_{est,1}$ using a variable r_c tends to perform better than the PM method with constant r_c . Although the improvement in the evapotranspiration estimation found in this work seems to be limited, the empirical approach involving r_c/r_a as a function of the square root of r^*/r_a , can be considered as an alternative to other approaches for modeling r_c . It may also be useful to incorporate the effect of variable canopy resistance into climatic and hydrological models.

5. CONCLUSIONS

The results presented in this work show that hourly ET_o estimates made with the Penman-Monteith equation and using a constant r_c value of 70 s m^{-1} , tend to underestimate measured ET_o during the summer period (when evaporative demand is high) and to overestimate it in winter (when ET_o is low), under the semiarid conditions of both the Ebro and Guadalquivir river valleys. This may have been a consequence of considering canopy resistance as constant during the day.

The issue is that Eq. (11), which is used to calculate r_c in a 'top down' approach, shows that r_c depends on environmental variables. Therefore, an approach that models r_c as a function of climatic conditions could be regarded as an alternative way of trying to overcome the limitations of the PM method. The Katerji and Perrier (1983) model proposed an r_c variable as a function of climatic

resistance r^* . They showed experimentally that there is a linear link with two empirical coefficients between r_c/r_a and r^*/r_a , and that this depends on climatic conditions.

The results presented here for semiarid regions with a Mediterranean climate show that estimating r_c as a function of the square root of r^* on an hourly basis, constitutes a better empirical approach than the linear option. In the case of the linear relationship, the values of the empirical coefficients calibrated for our semiarid regions were similar to those obtained by Steduto et al. (2003) for grass in southern Italy. This result suggests that in the proposed approach $(r_c/r_a)_{est,1}$, it may also be possible to extrapolate the locally calibrated empirical coefficients to other climatic regions.

When the different methods for estimating a variable r_c are used in the PM equation, the results show that estimates of hourly evapotranspiration $ET_{est,1}$ derived from the global validation data set tend to perform relatively better than ET_{PM} with constant r_c . The only apparent drawback is perhaps the fact that the minor improvement observed hardly justifies the effort to undertake the local calibration required. When the Todorovic mechanistic method for estimating r_c is used and applied in the PM equation, the results obtained show that, in comparison with the other methods, ET_{TD} also performs very well when it is used to estimate hourly evapotranspiration for our global data set.

Acknowledgements

This work was funded by the Spanish Ministry of Science and Technology under project REN2001-1630/CLI and by the Department of Universities and Research (Generalitat de Catalunya) under project 2001SGR-00306. The second author was also supported by a fellowship from the High Council of Research and Development of the Autonomous Government of Aragon. The authors would like to thank Jesus Gaudó, Miguel Izquierdo and Enrique Mayoral for their help with the fieldwork, and would also thank the reviewers for their comments that have helped to improve the final manuscript.

REFERENCES

- Alexandris S., Kerkides P. 2003. New empirical formula for hourly estimations of reference evapotranspiration. *Agric. Water Manag.* **60**: 157-180.
- Allen R.G., Jensen M.E., Wright, J.L., Burman, R.D. 1989. Operational estimates of evapotranspiration. *Agron. J.* **81**: 650-662.
- Allen R.G., Smith M., Perrier A., Pereira L.S. 1994a. An update for the definition of reference evapotranspiration. *ICID (International Commission on Irrigation and Drainage) Bulletin* **43** (2): 1-34.
- Allen R.G., Smith M., Perrier A., Pereira L.S. 1994b. An update for the calculation of reference evapotranspiration. *ICID (International Commission on Irrigation and Drainage) Bulletin* **43** (2): 35-92.
- Allen R.G., Pruitt W.O., Businger J.A., Fritschen L.J., Jensen M.E., Quinn F.H. 1996. *Evaporation and Transpiration*. In: ASCE, Hydrology Handbook, 2nd ed., ASCE Manuals and Reports on Engineering Practice No. 28: New York, 125-252.
- Allen R.G., Pereira L.S., Raes D., Smith M. 1998. *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No. 56: FAO, Rome, 300 pp.
- Alves I, Perrier A., Pereira L.S. 1998. Aerodynamic and surface resistances of complete cover crops: how good is the “big leaf”? *Trans. of the ASAE* **41** (2): 345-351.
- Alves I., Pereira L.S. 2000. Modelling surface resistance from climatic variables?. *Agric. Water Manag.* **42**: 371-385.
- Berengena J., Gavilán P., Márquez F. 2001. Precisión de las estimaciones de la ET_0 en un ambiente advectivo. *XIX Congreso Nacional de Riegos, 12 -14 June 2001, Confederación Hidrográfica del Ebro: Zaragoza (Spain)*, 67-68.
- Berkowicz R., Prahm L.P. 1982: Sensible heat flux estimated from routine meteorological data by the resistance method. *J. Applied Meteorol.* **21**: 1845-1864.
- Crawford T.M., Stensrud D.J., Carlson T.N., Capehart W.J. 2000. Using a soil hydrology model to obtain regionally averaged soil moisture values. *J. Hydrometeorol.* **1**: 353-363.
- Dickinson R.E, Henderson-Sellers A., Rosenzweig C., Sellers P.J. 1991. Evapotranspiration models with canopy resistance for use in climate models, a review. *Agric. For. Meteorol.* **54**: 373-388.
- Doorenbos J., Pruitt W.O. 1977. *Crop water requirements*. FAO Irrigation and Drainage Paper No. 24: FAO, Rome, 156 pp.
- Hall R.L., 2002. Aerodynamic resistance of coppiced poplar. *Agric. For. Meteorol.* **114**: 83-102.

- Huntingford C. 1995. Non-dimensionalisation of the Penman-Monteith model. *J. Hydrol.* **170**: 215-232.
- Hussein A.S.A. 1999. Grass ET estimates using Penman-type equations in Central Sudan. *J. Irrig. and Drain. Eng.* **125**(6): 324-329.
- Jarvis P.G. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. Roy. Soc. London, Ser. B* **273**: 595-610.
- Jensen M.E., Burman R.D., Allen R.G. 1990. *Evapotranspiration and Irrigation Water Requirements*. ASCE Manuals and Reports on Engineering Practice, No. 70. American Society of Civil Engineers: New York, 360 pp.
- Katerji N., Perrier A. 1983. Modélisation de l'évapotranspiration réelle d'une parcelle de luzerne: rôle d'un coefficient cultural. *Agronomie* **3**(6): 513-521.
- Katerji N., Itier B., Ferreira M.L. 1988. Etudes de quelques critères indicateurs de l'état hydrique d'une culture de tomate en région semi-aride. *Agronomie* **5**: 425-433.
- Kelliher F. M., Leuning R., Raupach M.R., Schulze E.D. 1995. Maximum conductances for evaporation from global vegetation types. *Agric. For. Meteorol.* **73**: 1-16.
- Kim J., Verma S.B. 1991. Modeling canopy stomatal conductance in a temperate grassland ecosystem. *Agric. For. Meteorol.* **55**: 149-166.
- Lecina S., Martinez-Cob A., Perez P.J., Villalobos F.J., Baselga J.J. 2003. Fixed versus variable bulk canopy resistance for reference evapotranspiration estimation using the Penman-Monteith equation under semiarid conditions. *Agric. Water Manag.* **60**: 181-198.
- Lee Y.H., Singh V.P. 1998. Application of the Kalman filter to the Nash model. *Hydrological Processes* **12**: 755-767.
- Linacre E. 1993. A three resistance model of crop and forest evaporation. *Theor. Appl. Climatol.* **48**: 41-48.
- Mayer D.G., Butler D.G. 1993. Statistical validation. *Ecol. Modelling* **68**: 21-32.
- Monteith J.L. 1965. Evaporation and environment. In: Fogg, G. E. (ed.), *The state and movement of water in living organisms*. Symp. of the Soc. for Exper. Biol., Vol. 19, Academic Press: New York, 205-234.
- Monteith J.L., Unsworth M. 1990. *Principles of Environmental Physics*, 2nd ed., Ed. Arnold: London, 291 pp.

Monteith J.L., 1995. Accomodation between transpiring vegetation and the convective boundary layer. *J. Hydrol.* **166**: 251-263.

Noilhan J., Planton S. 1989. A simple parameterization of land surface processes for meteorological models. *Mon. Weather Rev.* **117**: 536-549.

Pereira L.S., Perrier A., Allen R.G., Alves I. 1999. Evapotranspiration: concepts and future trends. *J. Irrig. and Drain. Eng.*, ASCE **125**(2): 45-51.

Perez P.J., Castellvi F., Rosell J.I., Ibañez M. 1999. Assessment of reliability of Bowen ratio method for partitioning fluxes. *Agric. For. Meteorol.* **97**(3): 141-150.

Perrier A. 1975. Etude de l'évapotranspiration dans les conditions naturelles. III Evapotranspiration réelle et potentielle des couverts végétaux. *Ann. Agronomiques* **26**: 229-245.

Perrier A., Katerji M., Gosse G., Itier B. 1980. Etude 'in situ' de l'évapotranspiration réelle d'une culture de blé. *Agric. Meteorol.* **21**: 295-311.

Peterschmitt J.M., Perrier A. 1991. Evapotranspiration and canopy temperature of rice and groundnut in southeast Coastal India. Crop coefficient approach and relationship between evapotranspiration and canopy temperature. *Agric. For. Meteorol.* **56**: 273-298.

Rana G., Katerji N., Mastrorilli M., El Moujabber M. 1994. Evapotranspiration and canopy resistance of grass in a Mediterranean region. *Theor. Appl. Climatol.* **50**: 61-71.

Rana G., Katerji N., Mastrorilli M., El Moujabber M., Brisson N. 1997. Validation of a model of actual evapotranspiration for water stressed soybeans. *Agric. For. Meteorol.* **86**: 215-224.

Rana G., Katerji N. 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *Europ. J. Agron.* **13**: 125-153.

Smith M., Allen R.G., Monteith J.L., Perrier A., Pereira L.S., Segeren A. 1991. *Report on the expert consultation on revision of FAO methodologies for crop water requirements*. FAO Land and Water Development Division: Rome, 54 pp.

Sommer R., Abreu Sa T.D., Vielhauer K., Araujo A.C., Folster H., Vlek P.L.G. 2002. Transpiration and canopy conductance of secondary vegetation in the eastern Amazon. *Agric. For. Meteorol.* **112**: 103-121.

Steduto P., Caliendo A., Rubino P., Ben Mechlia N., Masmoudi M., Martínez-Cob A., Faci J.M., Rana G., Mastrorilli M., El Mourid M., Karrou M., Kanber R., Kirda C., El-Quosy D., El-Askari K., Ait Ali M., Zareb D., Snyder R.L., 1996. Penman-Monteith reference evapotranspiration estimates in

the mediterranean region. In: Camp C. R., Sadler, E. J., Yoder, R. E. (Eds). *Proc. Int. Conf. On Evapotranspiration and Irrig. Scheduling, November 3-6 1996, at San Antonio, TX: USA*, 357-364.

Steduto P., Todorovic M., Caliendo A., Rubino P. 2003. Daily reference evapotranspiration estimates by the Penman-Monteith equation in Southern Italy. Constant vs. variable canopy resistance. *Theor. Appl. Climatol.* **74**: 217-225.

Todorovic M., 1999. Single-layer evapotranspiration model with variable canopy resistance. *J. Irrig. and Drain. Eng.* **125**(5): 235-245.

Ventura F., Spano D., Duce P., Snyder R. L. 1999. An evaluation of common evapotranspiration equations. *Irrig. Sci.* **18**(4): 163-170.

Verhoef A. 1995. *Surface energy balance of shrub vegetation in the Sahel*. Ph. D. Thesis, Wageningen Agricultural University: The Netherlands, 247 pp.

Verhoef A., McNaughton K.G., Jacobs A.F.G. 1997. A parameterization of momentum roughness length and displacement height for a wide range of canopy densities. *Hydrology and Earth System Sciences* **1**: 81-91.

Villalobos F.J. 1997. Correction of eddy covariance water vapor flux using additional measurements of temperature. *Agric. For. Meteorol.* **88**: 77-83.

Willmott C.J. 1981. On the validation of models. *Phys. Geogr.* **2**: 184-194.

Willmott C.J. 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **63**(11): 1309-1313.

FIGURE CAPTIONS

FIGURE 1.- The concept of surface resistance in the Penman-Monteith or 'big leaf' method.

FIGURE 2.- Locations of the study areas.

FIGURE 3.- *a)* Daily evolution of the aerodynamic (r_a) and canopy (r_c) resistances of grass for a specific day (March 5, 1999, Zaragoza). *b)* Experimental hourly averaged values for bulk surface resistance r_c for the calibration data set for Zaragoza. These were obtained by inverting the PM equation using values of latent heat flux measured by lysimeter (Eq. (11)). Hourly averaged values for climatic resistance r^* , available energy R_n-G and vapor pressure deficit D are also shown.

FIGURE 4.- Hourly values of evapotranspiration estimated using the PM equation (ET_{PM}) with a fixed r_c value of 70 s m^{-1} for the validation data sets of the measurement periods at each site (1:1 line is shown for comparison). Measured values (ET_o) were obtained with a weighing lysimeter (Zaragoza) and with an eddy covariance system (Córdoba).

FIGURE 5.- *a)* Comparison between variable canopy resistances $r_{c,TD}$ estimated by the Todorovic method and the experimental values r_c (diurnal period, Zaragoza). *b)* Hourly values of evapotranspiration ET_{TD} estimated with the variable resistance $r_{c,TD}$, compared with measured ET_o values for the whole validation period at Zaragoza.

FIGURE 6.- Variation of experimental values of r_c/r_a vs r^*/r_a on an hourly basis for the global calibration data set (Zaragoza and Córdoba) for: *a)* data corresponding to the diurnal period with $R_n-G \geq 0$ and β values in the interval $[-0.5, 0.5]$, *b)* data corresponding to the diurnal period with $R_n-G \geq 30 \text{ (W m}^{-2}\text{)}$ independent of the β values. The estimated values $(r_c/r_a)_{est,i}$ respectively correspond to estimating models 1 and 2 in Table 3.

FIGURE 7.- Hourly values of estimated evapotranspiration ET_{PM} (obtained from the PM equation with a fixed r_c value of 70 s m^{-1}) and $ET_{est,1}$ (obtained from Eq. (1) with the variable canopy resistance obtained from $(r_c/r_a)_{est,1}$), compared with measured values ET_o for the global validation data set (Zaragoza and Córdoba).

TABLES

Table 1. Representative values of the meteorological conditions during the measurement period at Zaragoza and Córdoba. T_x and T_n are maximum and minimum air temperature, respectively, and u is average wind speed.

Variable	Zaragoza			Córdoba		
	Average	Maximum	Minimum	Average	Maximum	Minimum
T_x (°C)	26.6	38.2	12.1	33.3	38.6	24.4
T_n (°C)	11.3	20.1	-2.6	18.2	22.7	9.2
u (m s ⁻¹)	2.1	7.6	0.4	1.7	3.6	0.7
% of days with $u > 4.0$ m s ⁻¹	9.0			0.0		

Table 2. Simple linear regression ($ET_{est} = c_0 + c_1 ET_o$) and statistics of the comparison between estimated (ET_{est}) and measured (ET_o) hourly values of evapotranspiration (mm h⁻¹) at the two locations for the respective validation data sets. Estimates were obtained using the Penman-Monteith equation with a fixed r_c value of 70 s m⁻¹ (ET_{PM}), and with the variable canopy resistance $r_{c,TD}$ (ET_{TD}). Measured ET_o values were obtained using a weighing lysimeter (Zaragoza) and an eddy covariance system (Córdoba).

Method	Location	n [*]	c ₀	c ₁	R ²	RMSE(%)	MBE(%)	EF
			(mm h ⁻¹)	(dimensionless)				
ET_{PM}	Zaragoza	1776	0.013	0.87	0.97	23.8	5.50	0.961
	Córdoba	1392	0.022	0.89	0.98	18.7	0.74	0.976
ET_{TD}	Zaragoza	1776	0.004	0.97	0.97	20.6	0.20	0.971
	Córdoba	1392	0.014	0.94	0.98	16.0	-0.58	0.982

* n: number of hourly data; c₀: intercept; c₁: slope; R²: coefficient of determination; RMSE(%): relative root mean square error; MBE(%): relative mean deviation error; EF: modeling efficiency.

Table 3. Empirical coefficients locally calibrated for two functional forms of the dependence of r_c/r_a on r^*/r_a in Eq. (9): 1) for the experimentally found best-fit relationship $(r_c/r_a)_{est,1} = a_1 + b_1 \sqrt{r^*/r_a}$, and 2) for a linear dependence $(r_c/r_a)_{est,2} = a_2 + b_2 (r^*/r_a)$. As well as the Todorovic method $r_{c,TD}$, models 4 and 5 proposed by other authors and applied to our data have also been included for comparison purposes. The last three columns show the values of the statistics for the comparison between estimated and experimental values of r_c/r_a .

Model*	Function	n	a _i	b _i	R ²	RMSE(%)	MBE(%)	EF
			(dimensionless)					
1. $(r_c/r_a)_{est,1}$	Square root	738	-0.66	1.38	0.72	48.6	-0.31	0.716
2. $(r_c/r_a)_{est,2}$	Line	738	1.1	0.19	0.55	61.5	-2.1	0.546
3. $r_{c,TD}$		738	-	-	-	85.0	37.3	0.133
4. Rana et al., 1997	Line	-	0	0.16	-	86.2	59.7	0.118
5. Steduto et al., 2003	Line	-	0.918	0.18	-	62.2	9.4	0.536

*n: number of hourly data; a_i: intercept; b_i: slope; R²: coefficient of determination; RMSE(%): relative root mean square error; MBE(%): relative mean deviation error; EF: modeling efficiency.

Table 4. Simple linear regression ($ET_{est} = c_0 + c_1 ET_o$) and statistics for the comparison between estimated (ET_{est}) and measured (ET_o) hourly values of evapotranspiration (mm h⁻¹) for the global validation data set (Zaragoza and Córdoba). Estimates of evapotranspiration were obtained from Eq. (1) with: a constant $r_c = 70 \text{ s m}^{-1}$ (ET_{PM}); a variable resistance $r_{c,TD}$ which were estimated by the Todorovic method (ET_{TD}); and a variable resistance obtained from the estimating methods $(r_c/r_a)_{est,1}$ and $(r_c/r_a)_{est,2}$ ($ET_{est,1}$ and $ET_{est,2}$, respectively). Measured ET_o values were obtained using a weighing lysimeter (Zaragoza) and an eddy covariance system (Córdoba).

Method*	n	c ₀	c ₁	R ²	RMSE(%)	MBE(%)	EF
		(mm h ⁻¹) (dimensionless)					
ET_{PM}	3168	0.017	0.89	0.979	21.4	3.15	0.969
ET_{TD}	3168	0.009	0.96	0.978	18.4	-0.18	0.977
$ET_{est,1}$	3168	0.006	0.91	0.982	19.8	6.18	0.974
$ET_{est,2}$	3168	0.005	0.90	0.977	21.8	7.16	0.968

*n: number of hourly data; c₀: intercept; c₁: slope; R²: coefficient of determination; RMSE(%): relative root mean square error; MBE(%): relative mean deviation error; EF: modeling efficiency.

FIGURE 1

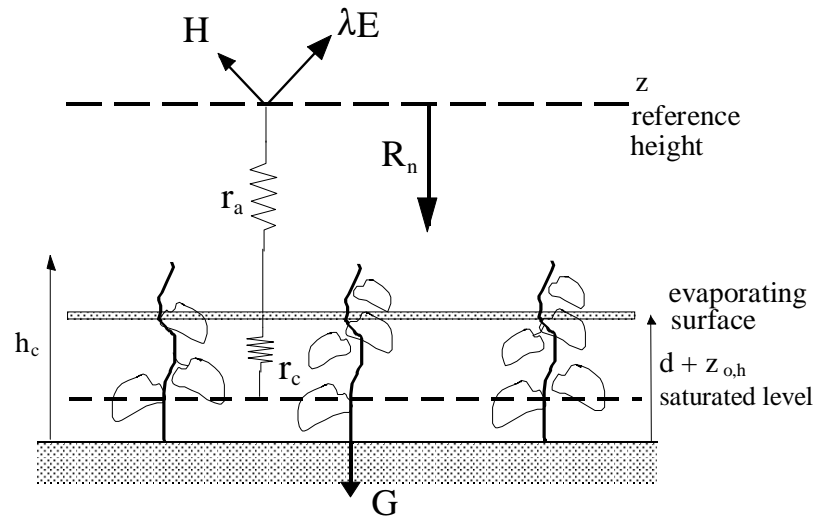


FIGURE 2

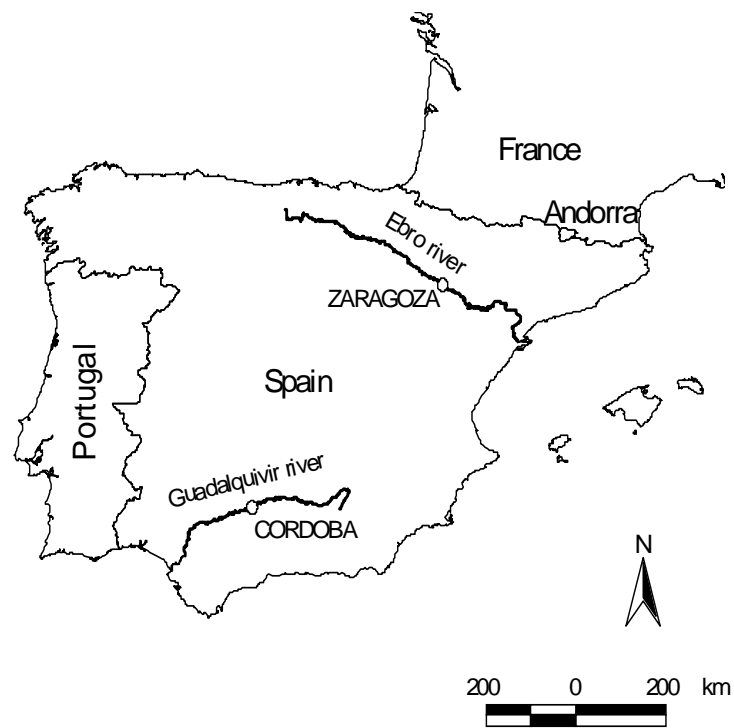


FIGURE 3

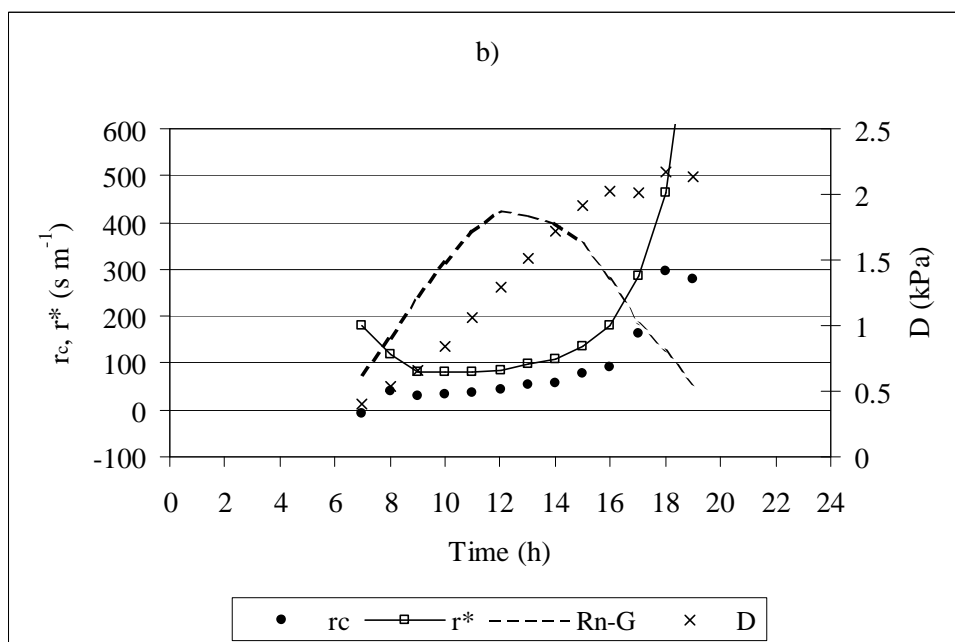
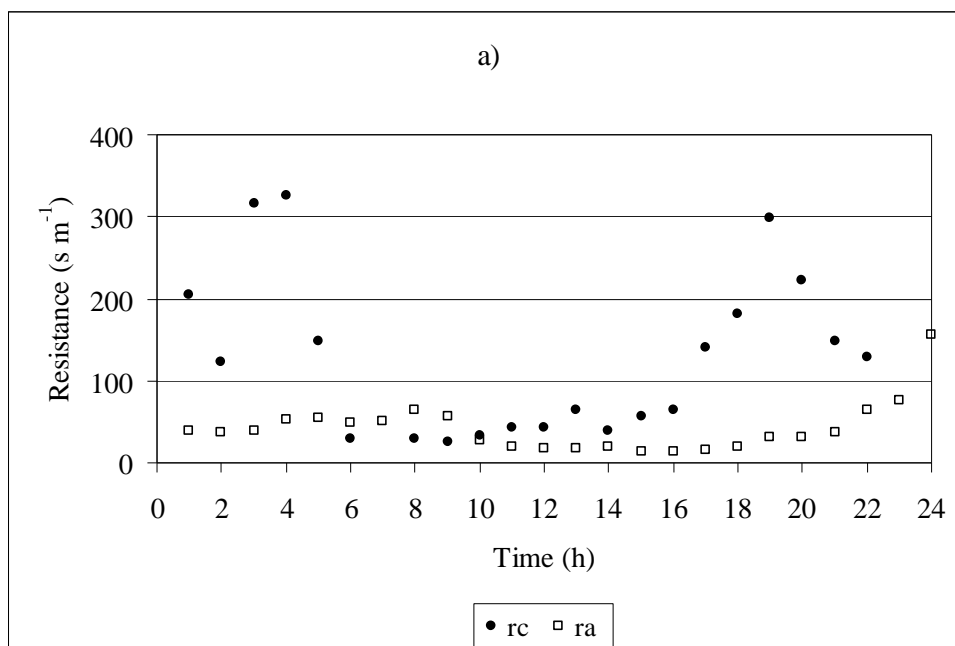


FIGURE 4

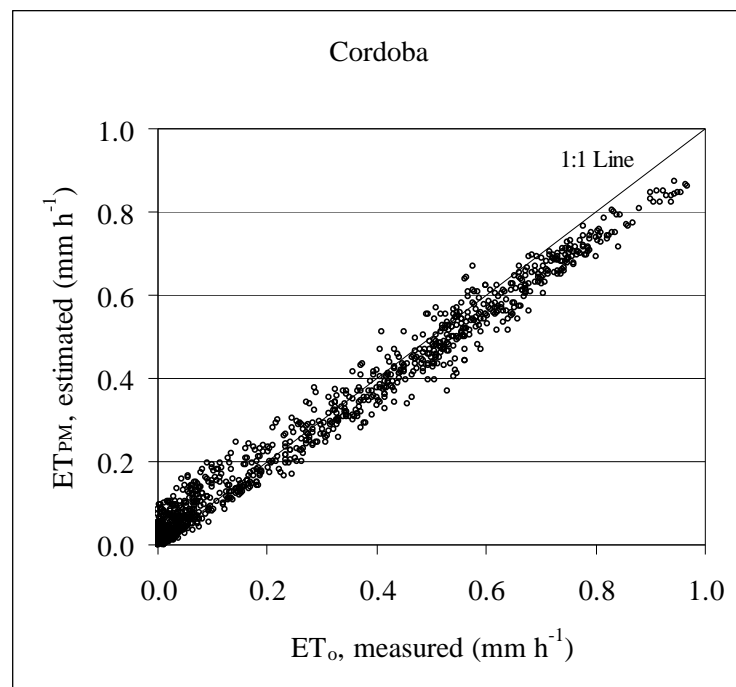
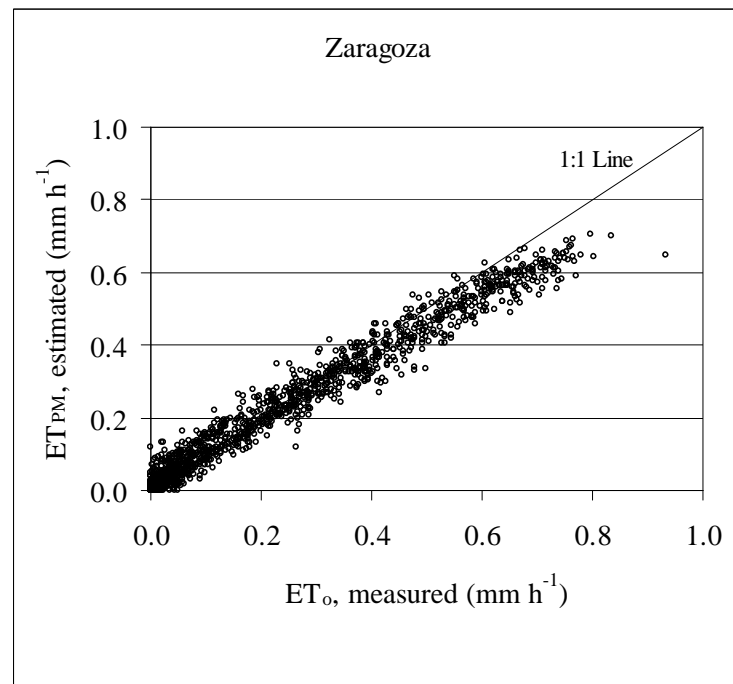


FIGURE 5

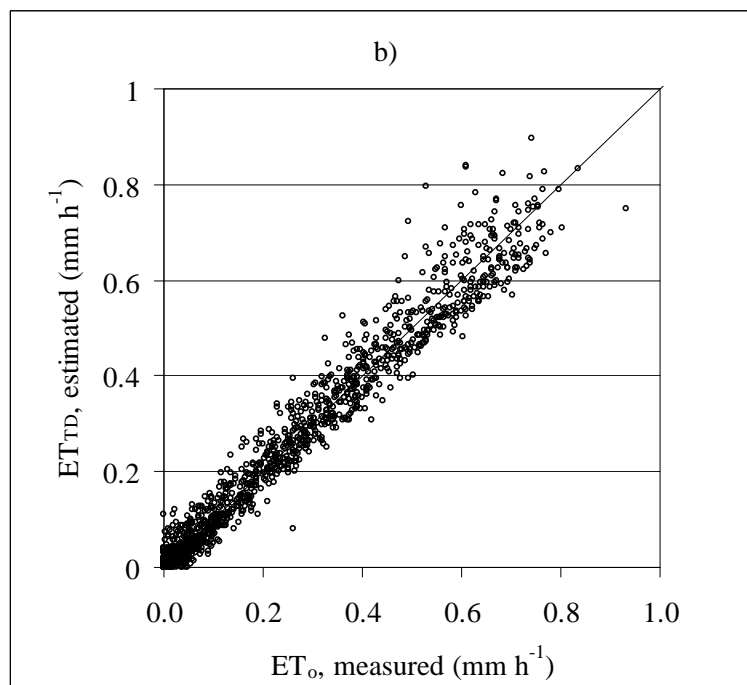
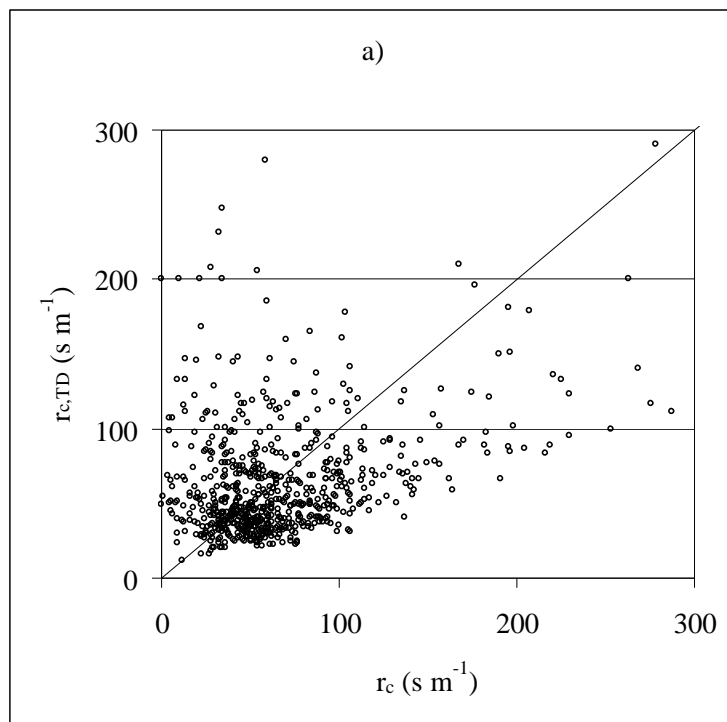


FIGURE 6

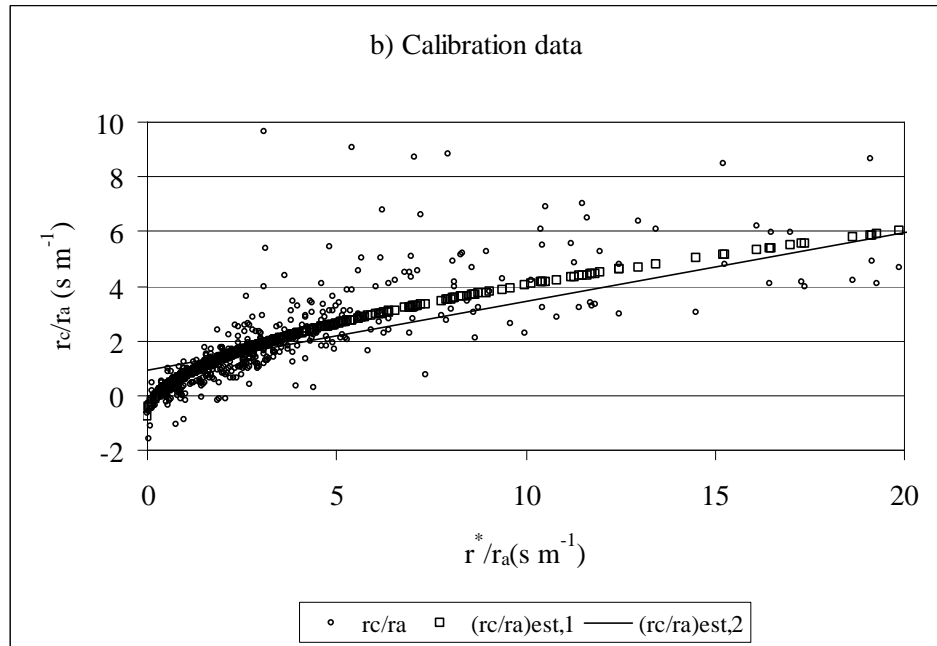
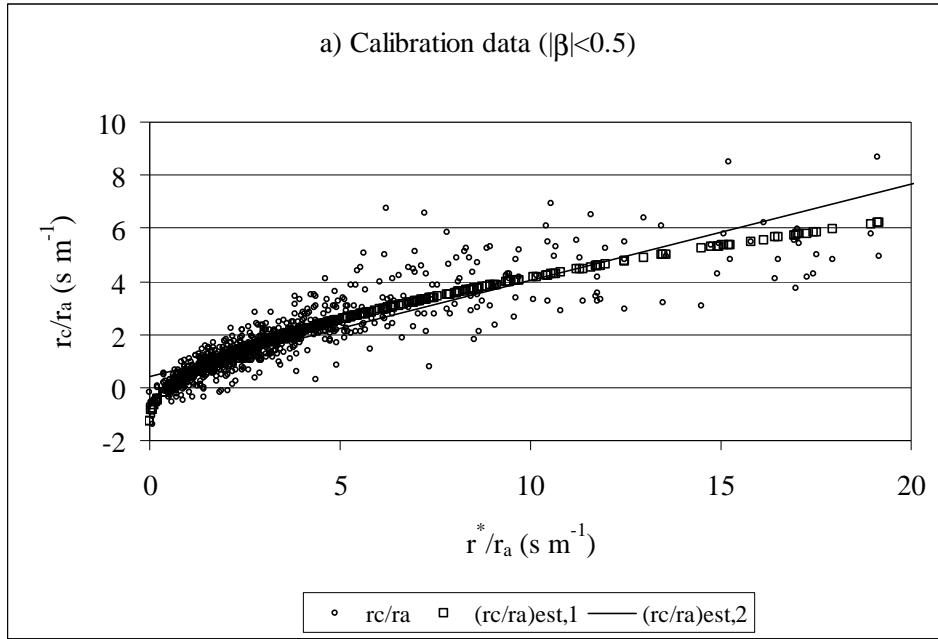


FIGURE 7

